SECOND SEMI-ANNUAL REPORT
on
RESEARCH ON

CONTROL OF A FREE-FLYING ROBOT MANIPULATOR SYSTEM

Submitted to
Henry Lum, Jr., NASA Technical Officer
Ames Research Center, Moffet Field, CA 94035

Prepared by
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Research Performed Under NASA Contract NCC 2-333
During the Period August 1985 through February 1986

Principal Investigator:
Professor Robert H. Cannon, Jr.

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INTRODUCTION

This report reviews work performed during the second 6 months of the subject contract by the Stanford Aerospace Automation Laboratory for NASA's Ames Research Center. The goal of our research is to develop and test control strategies for self-contained, autonomous free flying space robots. Such a robot would perform operations in space similar to those currently handled by astronauts during extravehicular activity (EVA). Use of robots should reduce the expense and danger attending EVA both by providing assistance to astronauts and in many cases by eliminating altogether the need for human EVA, thus greatly enhancing the scope and flexibility of space assembly and repair activities.

The focus of our work is to develop and carry out a program of research with a series of physical Satellite Robot Simulator Vehicles (SRSV's), two-dimensionally freely mobile laboratory models of autonomous free-flying space robots such as might perform extravehicular functions associated with operation of a space station or repair of orbiting satellites. (It is planned, in a later phase, to extend our research to three dimensions by carrying out experiments in the Space Shuttle cargo bay.)

During the second 6 months of the current contract we have continued the work on the dynamic control of the existing SRSV that was described in our previous report. In addition, we have proceeded with initiatives in path planning and obstacle avoidance, as well as multiprocessor computer architectures aimed at bringing greater computing power to bear on the problems of dynamic and strategic control. These programs are aimed at the creation of intelligent autonomously navigated robots as well as of robots with multiple, cooperating manipulators.

The SRSV Robot Model

Our control research is focused on a laboratory model of an orbital robot. (See Figure 1.) The main body of the robot is represented by a two-foot-diameter air-cushion vehicle, supported on a film of gas approximately .005 inches thick. The gas film is maintained between the base of the vehicle and a large granite surface plate (table) measuring 6×12 feet and ground flat to an accuracy of .001 inches. The base of the vehicle is also machined flat to .001 inches. The table is carefully leveled to eliminate gravity-induced

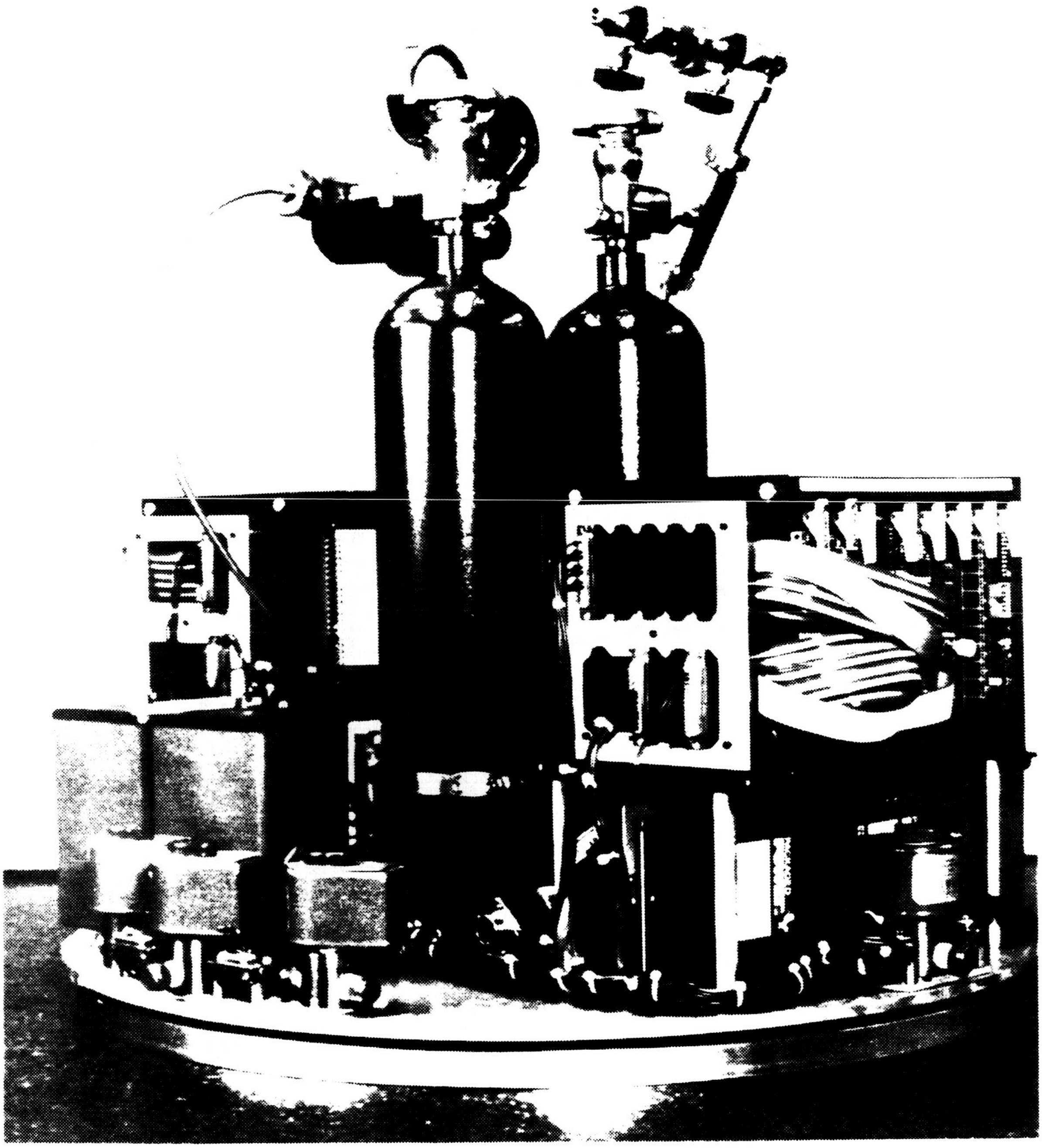

Figure 1: *The Satellite Robot Simulator Vehicle is shown in an early form without its arm. The computer is shown to the right; one of the two batteries is shown to the left behind a set of thrusters. The nitrogen tanks at center supply support and thruster gas.*

accelerations of the vehicle. The vehicle is equipped with eight thrusters for computer control of attitude and position. An angular rate sensor is also included to sense rotation of the main body.

Our laboratory model, referred to as the Satellite Robot Simulator Vehicle (SRSV), is a two-dimensional experimental model of a satellite robot, with five degrees of freedom. It is currently equipped with a single two-link arm whose joints are supported on individual air-cushion pads and operate in the two dimensions of the granite table surface. Each joint of the arm is equipped with a direct-drive brushless torque motor for control and an optical encoder for angle sensing. A television camera locates targets that are marked with infrared light-emitting diodes. Experimental results from the control of the SRSV will serve as a foundation for extending control methods to the case of actual space robots with nine or more degrees of freedom. We intend to demonstrate control of a dynamic simulation of a full three-dimensional satellite robot, using the same type of control algorithms as we will test with the SRSV.

PROJECT RESULTS

This section of our report reviews progress in building this laboratory test system. The mechanical design of the model is covered in an earlier report[1]. Recent advances have been in the area of control software development and computer communication. Control algorithm development work is still at an early stage and will be covered in the next report.

Advances in Computerized Control

The Satellite Robot Simulator Vehicle is equipped with an on-board computer based on the Intel 8088 microprocessor and built on the STD microcomputer bus. The computer includes the 8087 numeric data coprocessor, which is capable of fast floating-point arithmetic with very high precision. The STD bus makes it possible to add various analog and digital interfaces to the computer for control of the SRSV. As the 8088 processor is also used in the IBM PC personal computer, many tools are available for software development for that processor.

The on-board computer system as received included a primitive software package for loading and debugging programs from the IBM PC. This package suffered from several faults. Since the system used serial communications to perform program downloading, it could take up to forty seconds to transfer a single program. Also, no provision was made for the substantial operating system support that higher-level languages such as Fortran and C require in order to function. As a result, only simple programs written in assembly language could be used. Finally, no capability existed for the transferring of data from the on-board computer to the PC for display or recording.

In order to solve the problem of speed, we purchased the *Ultra-Link* fast parallel communications link to join the PC and the on-board computer. This link provided very high speed intercomputer communications, but it lacked the sophisticated software necessary for achieving the functions described above. Hence, we wrote a program loader that is capable of transferring a 30-Kbyte program within four seconds. Using the on-board computer's own system for debugging programs after they are loaded, we then had the ability to quickly load and test assembly language programs.

The problems of operating system support and data communications still remained. We solved both of these by emulating a subset of the PC's MS-DOS operating system in the STD bus computer. This was made possible by the fact that Fortran and C use only this restricted set of operating system function calls. As a result of this emulation, Fortran programs run on the on-board computer just as they do within the PC. Even keyboard, display, and file input and output perform just as they do on the PC. Therefore not only may programs written in high-level languages be run, but data collected may be written directly to disk files on the host computer for processing or display. Recently developed software even allows direct communication between applications programs running on the respective computers.

The operating system emulator, called UL-DOS, acts on system function calls by passing them through the parallel link for action by the PC. Depending on the call, register values and buffer contents are passed to exchange addresses, read/write data, buffer lengths, error codes and the like. The speed of the Ultra-Link bus allows such functions to be performed nearly as fast as they are for programs running directly on the PC.

Control of the Two-Link SRSV Arm

In order to exercise and test the control system capabilities of the SRSV, we have designed and implemented several controllers for the two-link arm. These controllers, mostly of a fixed-gain and decoupled variety, have demonstrated the need for a more sophisticated approach to control of the SRSV. Even for the relatively simple case of the fixed SRSV base, such controllers are quite susceptible to parametric variations and dynamic interactions due to motion of the arm.

In addition to the early experimental results mentioned above, Figure 2 shows an example of the simulated response of the SRSV arm to a simple slew command, with the "base" floating. Initially translating to the right, with zero rotation of base or joints, the arm is controlled to approach and remain at a fixed location. Note that this example shows the response of the base of the robot to the reaction forces generated by the arm, and the well-controlled slew and approach to the target.

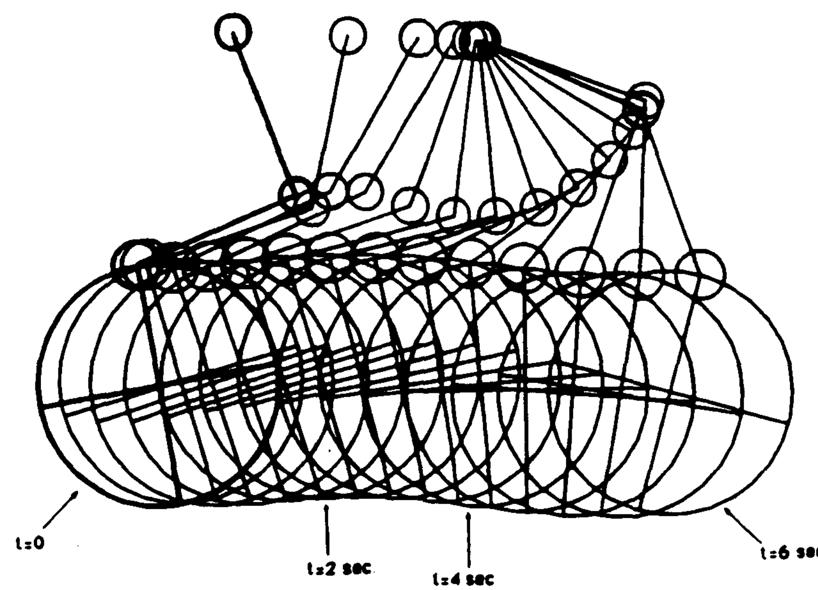

Figure 2: *Simulation results for the full 5-degree-of-freedom SRSV arm controller. The arm has been commanded to approach and hold at a target, from initial conditions which have the vehicle translating to the right at .25 m/sec.*

The simulation shown in Figure 2 was conducted prior to this report period with the help of the SDEXACT dynamic simulation program. We are currently working on developing an efficient formulation of the dynamic equations for the control algorithm, in order to compute them in real time. The equations must also be modified in order to work efficiently with frames of reference fixed to the SRSV rather than to the laboratory.

The initial control experiments have demonstrated that the current arm joint motors have too much friction and too little torque capacity for high-performance control. We are therefore obtaining higher-torque, limited-angle brushless motors for a new arm that will provide enhanced control as well as greater dynamic coupling with the base body of the SRSV due to its greater mass. The limited-angle motor operates with no commutation of the stator current, allowing torque to be exerted on the permanent-magnet rotor through an angular range of ± 60 deg from a central position. The lack of commutation brushes eliminates the usual friction that they induce.

Global Control and Task Planning

The research being conducted under this contract is intended to demonstrate the feasibility of small, autonomous space robots capable of moving to a work site under their own power and control and then performing required tasks with their various manipulators. Current research has thus far focused on the control of a two-link manipulator at the work site. For a fully automated system, the robots must be capable of traveling to the work site under their own control. It is desirable to have the entire sequence of events required for extra vehicular activity (EVA) under complete computer control with minimal input from a human operator. With this capability a single person will be able to oversee the operation of a colony of worker robots without having to leave the comfort and safety of a pressurized cabin. Ultimately the operator may be stationed on Earth rather than in space.

Similar capabilities are desirable for the next generation of automated factories here on earth. Most present-day applications of factory robots involve fixed-based machines operating in a limited work space. With the advent of the fully self contained mobile robot, greater flexibility exists for designing and operating a completely automated factory, particularly in the area of materials handling.

A clear need therefore exists for simultaneously controlling both the global motion of a robot as well as its various manipulators. This task requires a system level strategy for integrating and interpreting information from a variety of sources including a human operator providing task-level control.

Multiprocessor Robot Simulation

Continuing work in control of physical systems in our laboratory has demonstrated the feasibility of performing many aspects of control in parallel. The most notable to date has been the identification of a plant while controlling it using robust adaptive control[2]. Further divisions of control into separate tasks are possible by analysis of complex, disjoint systems (e.g. aircraft) or by means of spectral separation (e.g. fast manipulators attached to slow bodies [3]).

Not yet included in our control systems to date are higher level control functions (metacontrollers) which provide commands for low-level controllers. However, these functions definitely can be implemented in additional parallel processors.

This evolution of parallelism in control of more complex systems has led us to choose an expandable multiprocessor system for our continuing work in space robot systems control technology. This section of the report discusses the hardware and preliminary software assembled to implement a multiprocessor control system.

The system is currently based on an IBM PC-XT and an IBM PC-AT. The multiprocessor environment has been realized via the QNX real-time networking, multitasking operating system. This system provides inter-processor ethernet communications and operating system software for transparent internode communication. One of its many benefits is that intertask communication is handled in the same manner for remote tasks as it is for local ones. Therefore, a single CPU multitasking system is easily recast as a multiprocessor system.

The initial implementation with the current dual-processor system was a real-time dynamic simulation of a space robot. The configuration chosen for this simulation was a robot with a two-link arm and two "balance beams" for rotational control. This particular configuration was studied as a possible successor to the current SMS design.

This simulation architecture is very convenient because of the accessibility of system states and the ability to feed in control signals. This capacity makes it possible to implement new controllers without having to modify the system simulation code. Thus a common controller can be used both in simulation and for actual control of the physical plant by switching communications from the simulator to the physical plant. This capacity is particularly valuable in a research environment because the physical system is frequently being modified and is unavailable for control system testing. The simulator can also be used for anomaly detection in the operating plant, or for the evaluation of approach and manipulation maneuvers prior to execution.

Initial experiments have demonstrated the feasibility of separating parallel control-related tasks to run on multiple high-performance microcomputers. The computing performance obtainable is on the order of a superminicomputer at a fraction of the cost. The convenience of having an on-board computer integrated into a computer network also allows us to off-load much of the processing requirements from this one node. Furthermore, addition of more computing nodes to the system is an easy and low-cost method to upgrade our computing requirements over the course of our research.

EXPERIMENTAL PLANS

As detailed in the first section of this report, laboratory simulation is currently in the form of an Air Cushion Vehicle (ACV) based SRSV floating on a thin film of air over a large granite table which allows nearly drag free dynamics to be studied on Earth (in two dimensions).

In order to focus attention on the problems of navigation, obstacle avoidance, and fine position and attitude control, a second table having larger dimensions of 9×12 feet has been ordered. This second table will serve as the operating base for a new vehicle which will be substantially smaller and more deft than its predecessors.

The new vehicle is being designed with mobility as its most important feature. By scaling down the previous design and incorporating a more efficient propulsion system, the new vehicle will have an improved thrust to weight ratio allowing it to execute long trajectories in reasonable times. In particular, a new control valve/thrust-nozzle design is being pursued that will allow the use of much higher exhaust gas pressures. The vehicle will also incorporate a more sophisticated on-board computer system and will be networked via optical fiber to a set of off-board processors. This architecture will facilitate the implementation of a hierarchical control system.

To implement a global control scheme it is clearly necessary to have some type of global sensing system—the most logical of which is a vision system capable of tracking the relative motion of the robot, the robot manipulators, and the target object. To this end we propose using a new point tracking system with image processing and tracking software. It will run on an external computer system with a telemetry link to the on-board control system.

Operator commands to the robot will be entered from a user console using a mouse or other pointing device for delineating endpoints, targets, known obstacles, and desired waypoints. This strategic control will show that the human operator can interface with the autonomous robot at a very high level from a remote location. The system will incorporate a certain amount of onboard intelligence, in that it will be able to do path pre-planning, with real time correction to avoid obstacles that the robot encounters while executing a trajectory. New work in the areas of "Operational Space" control, path planning, and obstacle avoidance has recently been published that applies nicely to the scenario of an autonomous robot.

Once control of the new vehicle has been demonstrated, a two-link arm (and subsequently a pair of them) will be added. This arm will have an additional rotational degree of freedom at the wrist so as to have a full three degrees of freedom within a plane. This will actually yield a redundant system, since the craft provides us with an additional three degrees of freedom. We can take advantage of this redundancy to optimize the motions of both the craft and the arm while avoiding obstacles and kinematic singularities.

With the addition of the arm, the SRSV will be able to track and retrieve mobile targets which will themselves be self-contained, miniature ACV's. The targets will also possess active or passive identification markings to facilitate tracking. A vision system covering the immediate work space of the arm will also be added to the vehicle to facilitate endpoint control of the manipulator. This vision system can be based on the same principles as the global vision system.

In summary, the following aspects of global control and task planning are to be investigated:

- Simultaneous global and local control, using strategies for large and small motions.

- The trade-offs between using thrusters for global motion of the craft versus using the arm to accomplish a required task. In addition we will study whether both systems can simultaneously be used effectively.

- The effects of vehicle inertia when the manipulator and the vehicle have mass properties that are on the same order of magnitude.

- Strategies for implementing obstacle avoidance and human operator control at the task level.

Two unique aspects of this project involve:

- The combination of nonlinear bang-off-bang control of the linear vehicle dynamics with linear control of the nonlinear dynamics of the manipulator arm.

- A system-level or task-level problem description incorporating an AI type of approach as opposed to a pre-defined trajectory command.

In order to demonstrate the successful implementation of these concepts, we propose the following demonstration tasks. (The names and concepts are derived from football parlance wherein the objective is to acquire an object and move it from one place to another in an optimal way, so as to avoid a field of moving and adversary obstacles.)

- *The Fair Catch.* The ACV will use its arm but not its thrusters to snag a moving target. This requires matching both the position and the velocity of the target object at the time of pick up.

- *The Draw Play.* The ACV will pick up a fixed target (on the fly) while en route from a pre-defined starting point to a predefined ending point and deposit it to a user-specified destination in such a way as to minimize path time and/or control effort while satisfying any other imposed constraints.

- *The Pass Play.* While en route from pre-defined starting and ending points, the ACV will intercept a *moving* target and deposit it at a user-specified destination with a user-specified velocity.

These tasks can be further complicated by adding obstacles representing other space structures (or walls in a factory) that the control algorithm must contend with when designing and executing its course.

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